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QUANTITATIVE DETERMINATION OF HEAT TRANSFER FROM SEA TO AIR DURING PASSAGE OF HURRICANE BETSY

WILLIAM DRAKE WHITAKER

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QUANTITATIVE DETERMINATION OF HEAT TRANSFER FROM SEA TO AIR DURING PASSAGE OF HURRICANE BETSY

A Thesis

by

WILLIAM DRAKE WHITAKER

Lieutenant
United States Navy

Submitted to the Graduate College
of the Texas A&M University in partial
fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 1967

Major subject: PHYSICAL OCEANOGRAPHY

NPS ARCHIVE
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Thesis W5507

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Quantitative Determination of Heat Transfer from Sea to Air During Passage of Hurricane Betsy. (May 1967)

William D. Whitaker, B.S., United States Naval Academy

Directed by: Dr. Dale F. Leipper

ABSTRACT

An analysis has been made of the changes in heat content of the surface layers (above the 26°C isotherm) for a portion of the Gulf of Mexico in order to determine the total amount of heat transferred from the sea to the air during the passage of Hurricane Betsy in September of 1965. Estimations were made, at various distances from hurricane center, of the rate at which this heat was transferred.

ACKNOWLEDGEMENTS

The author of this paper wishes to express very special thanks to Dr. Dale F. Leipper for his generous assistance and direction, without which the completion of this work would not have been possible. This thesis was completed under sponsorship of the United States Naval Postgraduate School.

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CHAPTER I

INTRODUCTION

Review of the Literature

It is generally accepted among most oceanographers and meteorologists that the primary source of fuel for development and maintenance of hurricanes is provided by the oceans. The initial triggering mechanism is normally in the form of a preexisting low level tropical disturbance (Riehl, 1954). Further, it is thought that this fuel is provided in the form of latent and sensible heat transfers from the sea to hurricanes, at a rate far above that associated with normal atmospheric wind circulations characteristic of tropical and semi-tropical regions.

Kuo (1957) has constructed a mathematical hurricane model which requires "a warm ocean with a temperature higher than sea level air temperature, so as to give a continous flux of heat and water vapor from sea to air". Fisher (1957), in a study of five hurricanes in the Western Atlantic, has attempted to show that the behavior of these hurricanes was somewhat influenced by their proximity to local areas of relatively higher sea to air heat transfers. Riehl (1963), in examining the origins and possible modifications of hurricanes, has concluded that a rapid pick-up of latent and sensible heat is required for hurricane development and maintenance. Malkus (1962) provides an excellent summary of the air-sea interaction principles involved in

this transfer and concludes that the rates of transfer during hurricane passages are much greater than those for normal atmospheric conditions. Tisdale and Clapp (1963), in a study of hurricanes as related to air-sea interaction parameters, concluded that once a tropical disturbance had formed, the rate of transfer of heat from the oceans was instrumental in determining further development and growth. Perlroth (1966, unpublished manuscript), in a study of sea surface temperature patterns in relation to hurricane behavior, concluded that warmer sea surface tongues often indicated a deeper mixed layer, thereby providing a greater possible heat source for hurricane utilization.

Unfortunately in the studies cited above the investigators had access to little, if any, consistent oceanographic data for both before and after cases of hurricane passage. For the most part they based their work primarily on sea surface temperature charts gathered from any available source, including monthly mean SST charts and merchant ship data. Consequently, there was in effect no real knowledge of the amount of heat transferred from the sea to the hurricanes studied, a critical piece of missing information. This lack of knowledge of the heat transfer rates out of the oceanic environment can lead to rather different conclusions on the part of investigators. For instance Leipper (1967), in analyzing the after effects of Hurricane Hilda, reported a drop in surface temperature of up to 5°C in certain regions. Taken at face value this could mean an extraordinarily large amount of cooling and mixing at the surface. However, because he had access to

post-hurricane temperature-depth data in the form of numerous bathythermograph observations, he was able to show that this large drop was primarily the result of upwelling and not the result of heat transfer to the atmosphere. Stevenson (1965), analyzing Hurricane Carla, concluded that indeed there was a great deal of mixing and cooling in the surface layer. It is interesting to note that Jordan (1964), in a theoretical analysis of heat transfers associated with hurricanes, has indicated that the maximum possible decrease of sea surface temperature due to heat loss to the atmosphere, within 72 hours, is 2°F.

At the present time there exist only a few known attempts at a quantitative determination of these transfers. Malkus and Riehl (1960) have constructed a theoretical model of a moderate hurricane. Using the turbulent transfer equations of Jacobs (1941) they computed a figure of 3140 gm-cal/cm^2-day as the rate of heat transfer from the sea to their theoretical hurricane. In the only known case of actual data usage, Leipper (1967), using post Hilda data, estimated the heat loss to the hurricane in the region of Hilda's path to be on the order of 4150 gm-cal/cm^2-day. This estimation was based upon an analysis of post Hilda temperature-depth structure which indicated in which areas heat had been lost.

There have been many studies made attempting to tie the behavior of hurricanes to the oceans' heat transfer characteristics, but there is really no conclusive data concerning the magnitudes of this transfer based upon observed ocean thermal structures both before and after the passage of a hurricane.

Objective

The objective of this thesis is to make a study of a single hurricane for which data is available (Betsy, 1965) and attempt to determine, within the limits of this data, the actual amount of heat transferred from the sea to the hurricane during its passage.

CHAPTER II

APPROACH TO THE PROBLEM

Unfortunately the present state of technology does not permit one to actually enter an area where a hurricane is in progress in order to measure flux transfer characteristics, even if apparatus were available to take these measurements. Two cruises under the direction of Dr. Dale F. Leipper, Texas A&M University, by the university's research vessel R/V Alaminos, fortunately provided what is believed to be the best oceanographic data collection during periods just prior and just after the passage of a hurricane through oceanic waters. An additional cruise by the same vessel, planned and coordinated by Professor John D. Cochrane, Texas A&M University, provided substantial peripheral data for this investigation. Chapter IV includes the specific times, dates, and data utilized for each of the three cruises.

It was thought that if comparative temperature-depth data from the before and after situations were properly analyzed and applied, the total heat transferred from the sea to the hurricane could be computed based upon an observed change in total heat content of the ocean over a selected volume.

In order to clarify the remainder of this study, the following definitions are stated as they will be used here.

(1) The hurricane: This includes the actual region of hurricane force winds and the hurricane's associated wind field beyond this region, to the limits of the data.

(2) The selected volume will hereinafter be referred to as the area overlying the volume, meaning that computations will reflect changes in a water column, manifested as a per unit area value at the surface.

(3) The terms heat content and heat potential are synonymous in magnitude. They refer either to the ocean heat content of the volume of investigation, or to heat potential available in the ocean to the hurricane, each referred to 26° water. Specific cases may be determined from context.

There are a number of processes taking place during passage of a hurricane which would tend to change the total heat content of a column of water at any one location. Among these are mixing, advection, upwelling, and flux transfers to the hurricane itself. In order to determine the combined effect of sensible and latent heat transfers alone, the size of the other three factors would normally have to be known. However, if the thermal structure over a wide enough range of surface waters around the hurricane were known both before and after its passage, then this entire area could be treated as a closed system, the heat potential above a selected base level computed for the area both before and after the hurricane, with the difference being indicative of the heat transferred out of the oceanic environment. Mixing, advection, and upwelling would manifest themselves as a rearrangement or redistribution of heat within the area. A change in heat content at any specific location would be accounted for partially as a loss from the

ocean, and partially as a redistribution to some other location.

It was determined from an analysis of the data distribution of cruises 65-A-11, 65-A-12, and 65-A-13 that data were available for an area large enough to allow the utilization of this system of measurement of difference of heat potentials in the Gulf of Mexico. The actual selection of the area, a critical part of this study, is discussed in detail in Chapter III.

In order to compute heat potentials such that the final solution is manifested as a per unit area value at the surface, it is necessary to examine the problem in three dimensions. It was decided to make the base of the area (volume) under consideration not a constant depth, but rather a constant temperature. A temperature of 26°C was chosen for the following reasons. It is generally accepted that hurricanes form only over water of surface temperature greater than 26°C (Jordan, 1964; Byers, 1959; Ramage, 1959). This concept has been extended in this study to imply that, since a hurricane is primarily a thermal engine fueled from the sea (Malkus, 1962), it receives little or no fuel if the sea surface temperature falls below 26°C. Further, although an analysis of sea surface temperature patterns (Figures 1, 2) indicates a definite drop in sea surface temperature following the passage of Betsy, nowhere was the drop to a temperature below 26°C. The minimum surface temperature recorded was 26.9°C (BT No. 69, cruise 65-A-13). Therefore it can be assumed that water of a temperature less than 26°C probably provided no heat to Betsy.

That there was extensive upwelling associated with Betsy is reported by Leipper (to appear). His analysis of Hilda (1967) indicates that the appearance of upwelling occurs only late in a hurricane's passage, because of the time lag necessary for the formation of Ekman type currents. Therefore it is assumed that the upwelled water provided little or no heat to the hurricane. This is academic with regards to this study however, since a total change over a large area is being dealt with. During Betsy's passage the upwelling did serve to push the 26°C isotherm toward the surface in some areas (Figure 3, 4). This would mean that at a location where this occurred there would be a great change in heat potential. This would be compensated for by the warmer surface waters being pushed aside from this location into another area where they would possibly increase the heat potential of that area.

To summarize, the approach is to calculate the heat potential above the 26°C isotherm over a selected area both before and after the passage of Betsy, compensate for intra-oceanic redistributions of this heat potential by judicious selection of the area of investigation, and then utilize the difference between the two computed heat potentials as indicative of the heat lost to the hurricane.

CHAPTER III

SELECTION OF THE AREA OF INVESTIGATION

General

Since the entire problem was based upon taking the difference between two values of heat potential over a wide area of the Gulf of Mexico, it was imperative that the actual size and shape of the area be carefully chosen. The area had to be big enough so that it included as much of the Gulf as possible that was effected by Betsy, yet its size was inherently limited by the data available. Ideally there should have been data for the entire Gulf for both before and after the passage of Betsy, since the passage of a hurricane through a mediterranean sea acts in much the same way as a stone dropped into a pond, effecting the pond even to its furtherst extremities. Practically speaking it is very fortunate that there were any data at all bracketing the passage of a hurricane. A perusal was made of the 170 known hurricanes which developed in the Atlantic Ocean between 1941 and 1965 utilizing the positions as indicated by Tannehill (1956), Dunn (1956), Haggard (1959), Cry (1964, 1965), Cry and De Angelis (1965), in order to determine if any temperature-depth data were available for before and after situations. All of the data available in Texas A&M University's files were checked, along with the personal files of some of the staff members. A total of three cases were found which contained reasonable data. None of these cases was considered to have anywhere near ample coverage for

attempting a study of this type. Appendix A contains a listing of the particular hurricanes and other pertinent data.

The following is a listing of those factors which were considered most important in determining the final area to be utilized. A discussion of each factor follows the complete list.

(1) The data available.

(2) The path of the hurricane.

(3) The size of the hurricane.

(4) The speed of propagation and the force of winds.

(5) Upwelling.

(6) Hydrographic conditions and time lag between data collections and hurricane passage.

Available Data

Bathythermograph observations were available in varying amounts over an area bounded by the 84th and 94th meridians and the 21st and 30th parallels. However the distribution of data was such that there were no observations available south of the 24th parallel after Betsy's passage. Further there were no data collected in the northeast corner of the Gulf in the region bounded on one side by the Florida coast, and the others by the 27th parallel and the 86th meridian. Commencing with the 85th meridian (See Figure 5) and proceeding along Betsy's path, it can be seen that she passed through seven separate latitude-longitude squares, five of which contained observations both before and after

passage, and two of which contained observations collected only after passage. The squares to the north of the western section of her path contain a better distribution of data than those analagous squares to the north of the eastern section of her path.

Path of Hurricane

Betsy entered the Gulf on a westerly course on the morning of 8 September just south of the tip of Florida. At about 2200 (CST) on the evening of the 8th she turned approximately 15° to the right to a course of about 295°T. She maintained this course with some slight north and south meanderings until about 1000 on the morning of the 9th. At this time she again turned to the right to a course of about 324°T along which she proceeded, again with slight meanderings, until she went ashore at Grand Isle, La., at about 2100 on the evening of the 9th.

Because of the data distribution described above, it was decided to make the 082200 position of the hurricane (25.6N, 84.7W) a point through which would be drawn the southeastern boundary of the area to be investigated. This was a line perpendicular to 295°T, running in a 025-205°T direction. Her mean path was taken as described above and utilized as a two-sectioned axis, parallel to which the northeastern and southwestern boundaries of the area would be drawn. Finally, in order to avoid the problems associated with passage over land, the northwestern boundary was laid out as a line, perpendicular to 324°T, through a point just southeast of the extremities of the Mississippi

Delta region. Thus the combination of data distribution and hurricane path indicated in a general way what the final perimeter of the area would be.

Hurricane Size

Betsy was a relatively large hurricane having an eye approximately 35 N.M. in diameter, with hurricane winds extending out to about 75 N.M. from hurricane center. Therefore, in order to assess heat transfers on an areal basis, the radius of investigation would have to extend beyond 75 N.M.

Speed of Propagation and Force of Winds

As Betsy moved into the Gulf her forward speed increased such that she crossed the Gulf at an average speed of about 14.7 kts. The standard flux transfer equations are of the general form:

$$Fs = -\rho Ks \times \frac{d\bar{s}}{dz}$$

Where: s = property in question
z = dimension in question
K = a constant
ρ = density
F = flux transfer

The equations for transfer of sensible and latent heat fluxes from sea to air are derived from this basic equation. These (Malkus, 1962) are given as follows:

$$Qs = \rho c_p c_d (To-Ta) u_a$$

$$Qe = \rho L c_d (q_o - q_a) u_a$$

Where: Qs, Qe = transfer of sensible and latent heat, respectively

c_p = specific heat of sea water

c_d = transfer coefficient

T = temperature

o, refers to ocean surface

a, refers to elevation at which measurements were taken

u = wind speed

q = specific humidity

There is still much debate over the validity of the flux transfer equations. However, it will suffice to say here that at the air-sea interface, and close to the surface, where turbulent shear flow is the primary causal factor of exchange mechanisms, the flux transfers are generally linearly proportional to wind speed (Malkus, 1962). This is an important concept and will be utilized frequently in this paper.

Considering the cyclonic wind circulation associated with hurricanes, together with Betsy's average propagation speed of 14.7 kts, there is indicated a mean effective wind speed over the sea surface of about 57 kts in the right semi-circle and 44 kts in the left semi-circle of the hurricane (See appendix H). Therefore, locations along the right hand side of the hurricane's path should experience transfers approximately 57/44 (1.3) times those of locations at similar distances on the left hand side. This was an important factor in determining the distances to extend the radii of investigation on either side of the mean hurricane path.

Physically, with respect to the sea surface, one has an essentially circular wind field, whose velocity decreases as radius increases, but also along each circle there is an additional gradient around that circle. The entire system moving in a fairly constant direction causes the gradient around the circle. Therefore, instead of examining an area of equidimensional characteristics across the mean hurricane path, the area was skewed to the right hand side, thus compensating for differences in wind speed on either side of the mean path. By making this compensation, an overall average transfer rate can then be computed as though the wind field were symmetric with respect to the mean path. The 1.3:1 ratio was used to determine this skewness.

Upwelling

Generally speaking, upwelling is associated with eastern boundary currents such as the California and Peru Currents. Recently, however, upwelling has been determined to be associated with hurricanes. Fisher (1957) appears to have been one of the first investigators to notice this characteristic. Leipper (1967, to appear) has demonstrated upwelling features associated with Hurricanes Hilda and Betsy. Briefly, he has described the effect as caused by the partial formation of Ekman currents, which in turn are a function of the cyclonic circulations associated with hurricanes. Both he and O'Brien (1965) agree that the upwelling results in the displacement of the

warmer surface waters away from the central area of the hurricane's path. Therefore, in regards to this study of heat potential differences, upwelling must be taken into consideration.

Hydrographic Conditions and Time Lag

Betsy passed through an area containing an almost permanent cyclonic eddy (Figure 9). Because of the mean nine day time lag between hurricane passage and the post Betsy data collection, waters in the vicinity of the eddy would be subject to advection. The mean speed of the eddy was in excess of 1 kt, therefore the affected waters could have been transported a distance in excess of 200 miles from the time the hurricane passed, until the data was collected. However as indicated in Figure 9, almost the entire eddy, as defined by the depth of the 22°C isotherms (Leipper, to appear), is included within the area of investigation. Therefore changes in heat content caused by these circulations will be accounted for as redistributions within the area.

The final area selected, using the above concepts as a basis, totaled 274.60 km^2. The mean distance from the hurricane path was 150 N.M. on the right and 115 N.M. on the left. There were two latitude-longitude squares which showed high losses which did not fall entirely within the area. These, 24-86 and 24-87, because of their position, could not be wholly included without upsetting the

overall symmetry of the problem. However, if they had been entirely included, their additional contribution to the overall solution would have altered that solution by less than 1%.

In summary, in order to determine the actual amount of sensible and latent heat transferred to the hurricane from the sea, an area was selected which, for the most part, included not only those regions of maximum theoretical transfer, but also provided for movement of waters within the area affected by the hurricane. This provided a feasible situation in which simple differences of thermal characteristics (i.e. heat potential) could be used as a basis for determining the heat loss from the sea.

CHAPTER IV

COMPUTATION OF HEAT POTENTIAL

General

The specific heat of sea water as it varies with certain parameters is still open to question. In general it is thought to increase with increasing salinity and temperature, and decrease with increasing pressure. For this study the average salinity of the water was approximately 35 $^{0}/_{00}$, the depth varied from sea surface to a maximum of 150 meters, with temperatures ranging from 30+°C to 26°C. Dietrich (1957) indicates a specific heat of about 0.995 $\frac{cal}{gm\text{-}°C}$ for this range of values. Based on this it was decided to use a simple value of 1 $\frac{cal}{gm\text{-}°C}$ for the entire study, as any variances would produce errors so small as to be considered negligible.

Basic Data

Bathythermograph readings provided the major source of data for the problem. A total of 624 BT's were utilized from three separate cruises by Alaminos. The cruises bracketed Betsy's passage in time from 28 days before, to 14 days after, her traverse of the Gulf. The actual cruise times and BT's utilized are broken down as follows:

Cruise No.	Dates (inclusive)	No. BT's used
65-A-11	10-24 August, 1965	298
65-A-12	30 Aug - 8 Sep, 1965	105
65-A-13	11-25 September, 1965	221

The BT's were first grouped by position, i.e. in one degree squares of latitude and longitude so as to form a grid system. The number of observations in any one grid square ranged from a low of (1) to a high of (33) as indicated in figure 5. Next an average BT was constructed for each grid square. No greater value was placed upon a square having a large number of observations, than one having few, except those grid squares having only one observation (of which there were 5) were not utilized as representative of an entire square, but rather were plotted at the point of collection. There were a total of 61 grid squares having at least one observation.

The average BT's for each grid square were constructed by a method which would provide for a simple means of computing heat potential. The details of the actual construction are discussed in Appendix B.

Method of Computation

The computation of the heat potential for each grid square where data was available was accomplished through the use of a specially constructed nomogram. The nomogram was based upon the application of Simpson's Rule and the simple heat content formula:

$$Q = \overline{\rho C T h}$$

Where: ρ = density, taken as 1 $\frac{gm}{cm^3}$

C = specific heat

T = temperature

h = depth of incremental layer

Appendix C contains a detailed discussion of the computation method.

Application to Geographic Locations

A total of 403 BT's were utilized to determine the heat potential prior to Betsy. These were distributed throughout 42 grid squares having an area of 456,775 km^2. Appendix E contains a complete listing by grid square of the number of observations; average, maximum and minimum surface temperature; average, maximum and minimum depth of the 26° isotherm; and the computed heat potential per cm^2.

A total of 221 BT's were utilized to determine the heat potential after Betsy within 28 grid squares having an area of 304,520 km^2. Appendix F contains the same type data for the situation after Betsy as does Appendix E for the prior case.

For each situation contours of constant heat potential were drawn on charts of scale 23 cm = 60 N.M. These contours were determined by assuming that the average heat potentials computed were located at the geographical center of each square. The heat potentials of those squares containing no observations were estimated from the contours. The final heat potential value assigned for each grid square within the area under investigation can be found in Appendix G.

Figures 6 and 7 show the results of contouring. Figure 8 indicates contours of change in heat potential from before to after Betsy's passage.

CHAPTER V

DETERMINATION OF HEAT TRANSFERRED

The final determination of heat transferred from the ocean to Hurricane Betsy during her passage over the Gulf was a relatively simple matter, once the preliminary work outlined in the first four chapters was accomplished. Appendix G indicates the total computed change in heat potential over the area of investigation. This amounted to 488.81×10^{16} gm-cal, over a total area of 274.70×10^{3} km^2. The average loss on a per unit area basis was therefore computed to be:

$$488.81 \times 10^{16} \text{ gm-cal} / 274.70 \times 10^{13} cm^2$$

or

$$1770 \text{ gm-cal}/cm^2$$

The computed figure of 1770 gm-cal/cm^2 includes normal seasonal heat exchange between the atmosphere and the ocean. There has been no seasonal study of the changes in total heat content of the Gulf of Mexico. It is believed that the change in heat content of the Gulf on a month by month basis is such that it would effect the above figure very little for the period of data collection (10 August through 25 September). This is strictly an assumption, but one that must be made for lack of information. However the assumption is based upon three factors which lend some support to it.

It has already been stated that the rate of heat transfer from sea to air is much greater for hurricane situations than for normal atmospheric conditions. Therefore the loss figure computed should ipso facto be much greater than would be incurred as a result of normal atmospheric conditions. Thus the addition or subtraction of seasonal exchanges applied to the computed figure would not be expected to alter this figure by a great amount.

Dietrich (1957, after Albrecht, 1940) shows that for data analyzed in the Florida Straits near Key West, Florida, the total heat content of this region increases up until about the 1st of September, at which time it begins to decrease. The rates of additions and depletions range from about 80 gm-cal/cm^2-day at the beginning of August (a gain) to about 100 gm-cal/cm^2-day at the beginning of October (a loss). The mean data collection date for the Betsy investigation was 31 August - 1 September. If the Key West analysis held for the entire Gulf, then one could say that the effect of seasonal heat exchanges upon the present study was negligible.

Net change in heat content of the oceans is mainly a function of solar radiation received at the sea surface. Because the Gulf of Mexico is north of the Caribbean Sea, the maximum solar radiation received by the Gulf, considering the summer and fall months, would occur earlier in the calendar year than the maximum in the Caribbean. It would thus be expected that maximum sea surface temperatures and maximum heat content would also occur earlier in the Gulf than the Caribbean.

Leipper (1954) shows that the mean sea surface temperatures in the Gulf reach a maximum in August. Colon (1960), in a study of the heat budget of the Caribbean Sea, shows that sea surface temperatures and heat content reach a maximum in September. Comparing the temperature maxima of the Gulf and Caribbean and considering their relative geographic positions, it is probable that the maximum heat content of the Gulf is attained in August. If this be the case then it is quite likely that the Betsy study was little affected by normal seasonal heat exchange. This is concluded because the period of data collection (10 August to 25 September) was probably one over which a net gain in August was compensated for by a net loss in September.

Therefore the net daily change in heat content of the Gulf during the period of this study was probably one of low value, ranging from a net daily gain to a net daily loss, the final result of the daily change having little effect upon the computed figure of 1770 gm-cal/cm^2.

Using the computed value of heat transferred to Betsy stated above, an attempt was made to determine the actual rate of transfer at various distances from hurricane center. Because of the use of the assymetrical area with respect to mean hurricane path, the overall rate of transfer can be simply computed by determining the time required for Betsy to pass through the area. This time was about 21.5 hours. Therefore the average rate of transfer over the entire area was computed to be:

1770 gm-cal/cm^2 x 24 hours/21.5 hours

or

1990 gm-cal/cm^2-day

The computation of transfer rates at specific distances from hurricane center is much more complex. The general method used was much simplified and involved construction of an estimated wind profile for Betsy, and use of the concept of proportionality between flux transfers and wind speed. The details of the wind profile estimation are discussed in Appendix H. The details of the transfer computations are discussed in Appendix I. The final results of these computations are indicated below. The edge of the eye was estimated to be 16 N.M. from hurricane center. The region of maximum winds was estimated to be 33 N.M. from hurricane center.

Average Transfer Rates

Distance from Hurricane Center (N.M.)	Average Rate of Transfer (gm-cal/cm^2-day)
0 - 16	0
16 - 33	2020
33 - 48	3730
48 - 64	3070
64 - 90	2360
90 - 125	1790
125 - 150	1430

CHAPTER VI

DISCUSSION OF CONTOUR CHARTS

The three heat potential charts (Figures 6, 7, 8) representing the heat potential above the 26° isotherm will be discussed within the framework of gross trends with respect to Betsy.

The contours for the situation prior to Betsy indicate a large area of high heat potential in the east central Gulf, approximately centered over the eddy. This area was characterized by surface temperatures above the average (29.2°C) for the entire area. The depth of the 26°C isotherm was in general deeper than the average (53M) for the entire area. This is a situation which Perlroth (1966, unpublished manuscript) referred to in his recent work; i.e. that higher surface temperatures would be reflected in subsurface layers. On the western side of this large heat source were three smaller areas, all containing a great deal less heat potential than the central area. Betsy's path carried her across the entire northern half of the large heat source, however no inference will be drawn from this.

An examination of the heat potential contours following Betsy's passage indicates a rearrangement of the contours, with a general decrease over all, except for an increase in the northern section of the Gulf.

The most informative chart is Figure 8, depicting the change in heat potential from before to after Betsy's passage. First, approxi-

mately along her mean path, there is a band showing less change in heat potential (less than 2000 gm-cal/cm^2) than those areas either side of her track. This is to be expected since the path over which the eye passed experienced a period of no winds, and periods of approximately equal and opposite winds. These opposing winds would tend to negate the effects of upwelling. Second, proceeding away from Betsy's mean track on either side, there is an immediate large increase in heat potential change. This is indicated by a maximum change (a loss) of 9000 gm-cal/cm^2 in an area parallel to her track. It appears that the hurricane slowed here while making her turn to the north. The inference is that if she did slow, then more time was spent in the region, and hence more heat was actually removed from the ocean. Further, Ekman currents would have greater opportunity to form, which in turn would contribute to an increased loss at any location in this region. On the northern side of this "heat loss bulge" there is a band wherein the amount of loss decreases to no loss, beyond which there is a sizeable gain in heat potential. This can be explained in conjunction with the before and after sea surface temperature charts and depth of 26°C isotherm charts (Figures 1, 2, 10, 11). The region on the change chart indicating a gain in heat potential shows little change in sea surface temperature before and after Betsy's passage. This suggests that probably not a great amount of heat was removed from the surface layers by the hurricane. This is quite logical when it is considered that the winds in this region were much reduced compared to those near the

central area of the hurricane. However, the depth of the 26°C isotherm in this region shows a marked increase. A possible cause of this is mixing, downwelling or a combination. O'Brien (1965), in his theoretical model, indicates that upwelling can occur beyond the radius of hurricane force winds, with downwelling beyond this. Therefore it is highly likely that this increase in heat potential was caused by transport of surface waters into these regions. As the hurricane passed by, the waters in the central areas were cooled more than the waters at the extremities, therefore their surface temperature at the same point in time should have been less. Late in the hurricane's passage, if upwelling developed, these central surface waters would be forced out from the central region, leaving behind a still colder surface water. The temperature chart following Betsy's passage indicates lowest temperatures near the central region of the hurricane passage, and slightly warmer temperatures further out from her mean path. The surface waters forced away from the central region were therefore warmer than the waters remaining, but colder than the waters toward which they were proceeding. The situation developed in which cooler surface waters were transported into an area of warmer surface waters, with the result that mixing and possibly downwelling took place, which was manifested as a deepening of the isotherms. Since the minimum recorded temperature in the central area was greater than 26°C, the displaced waters must have been of a temperature greater than this, therefore any region to which they proceeded would receive an input of heat potential

as defined in this study.

It has been stated that the effects of Betsy with regard to changes in heat potential should be greater on the right side than on the left side of her mean path. This is true in general. The exception is the very large change in heat potential south of the eastern axis. This extremely high change is attributed in part to the eddy effect. It may be seen from the pre-Betsy heat contours that the path of the eddy would tend to move water of lower heat potential into an area of extremely high heat potential, with that water then moving on around with the flow. Because of the time lag between pre-Betsy and post-Betsy data collections, it is believed that this occurred such that these particular contours show what could be called an abnormally high apparent heat loss in this southern region.

CHAPTER VII

CONCLUSIONS

The simple conclusion has already been stated in Chapter V. That is, the amount of heat transferred from the sea to the air during the passage of Hurricane Betsy was 1770 gm-cal/cm^2 over the area investigated.

The heat transfer rate arrived at of 3730 gm-cal/cm^2-day for the hurricane force wind area was computed utilizing an estimated wind profile. However it is in close enough agreement with Malkus and Riehl (1960) and Leipper (1967), so that it can be assumed to be reasonably accurate.

Therefore it is thought that future investigators may assume for rates of heat transfer from the sea to hurricanes, a figure somewhere within the range of 3000-5000 gm-cal/cm^2-day, when dealing only with the region of hurricane force winds.

Finally it is believed that the heat potential approach is a fairly novel one and provides investigators with an additional tool for viewing overall changes in surface layers associated with short term atmospheric influences.

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APPENDIX A

HURRICANE DATA SUMMARY, 1941-1965

Hurricanes, 1941-1965, for which before and after temperature depth data is available. Designations after Tannehill.

Designation	No. of Observations	Collected by (ship)	RMKS
2-41	28	Capella	70' BT
1-43	44	Blanco	400' BT
8-47	47	Wilke Penn State Robinson Sarsfield	400' BT

APPENDIX B

CONSTRUCTION OF AVERAGE BATHYTHERMOGRAPHS

The BT's were read from corrected polaroid photographs from the surface to that depth at which the water temperature had decreased to 26°C. Surface temperature data were utilized exclusively from BT readings, rather than thermograph or bucket readings, because of the necessity of preserving the correct relationship between surface temperature and the depth of the 26° isotherm.

The surface temperature readings were averaged to give a representative surface temperature for each grid square. This was designated To. The depth of each BT within a grid square was then read at an increment of one-half degree below its individual surface temperature. These depth readings were averaged and assigned a temperature of To - 1/2. This process was continued at increments of one-half degree until To - 2 was completed. Finally the depth of the 26° isotherms were tabulated and averaged to give an average depth corresponding to that temperature. This method tends to distort the temperature-depth structure slightly, since it does not allow for an isothermal layer, i.e. the BT's are read as though the temperature gradient changes linerarly in segmented elements between increments of temperature. The averaging process tends to smooth out these distortions so that although the final product is not representative (in shape) of a typical BT for any grid square, it is a fairly accurate representation of an average temperature-depth relationship for the square. The average BT

obtained was then used as the basis for determining the heat potential above the 26° isotherm.

The following is an illustration of the method used for determining average BT's for each grid square. The example is from data collected in grid square 26-89; 5 BT's collected during cruise 65-A-13.

BT No.	150	151	152	153	154	$\bar{A}$
To	29.0	28.5	28.8	28.9	28.9	28.8
To-1/2	48	42	42	37	33	40
To-1	49	43	43	38	35	42
To-3/2	50	43	44	40	37	43
To-2	51	45	46	41	40	45
26°	54	47	49	43	42	47

Thus the average temperature-depth structure assigned to area 26-89 is as follows:

Depth (m)	Temperature (°C)
0	28.8
40	28.3
42	27.8
43	27.3
45	26.8
47	26.0

APPENDIX C

METHOD OF CALCULATION OF HEAT POTENTIALS

Because of the large number of heat potentials to be calculated, a special nomogram was constructed (Figure C-1) based upon Simpson's Rule:

$$Q = \frac{\Delta x}{3} (y_o + 4y_1 + 2y_2 + 4y_3 + y_4)$$

Where: Q = the heat potential of a water column in gm-cal/cm^2

Δx = the interval of 1/2°C

$y_o \cdots y_4$ = the depth in meters corresponding to each temperature increment

The nomogram incorporates the 1/2° temperature interval, the specific heat, and the division by 3. Since the process of averaging BT's smoothed the temperature-depth relationship for each grid square, it was thought that use of Simpson's Rule with an even number of intervals would provide a rapid means of computing heat potential if applied to a nomogram. For each average BT there were tabulated intervals of depth from the surface to a depth of a 2°C temperature change. In order to calculate the heat potential of a water column above a depth of a 2°C temperature change the procedure is as follows. Set the initial depth (surface) equal to zero, therefore the first term of the equation is zero. The depth corresponding to To - 1/2 is then lined up across the nomogram and the heat potential for this increment is read from the 44 column. Likewise the next intervals are read from the 24, 44, and

4 columns respectively. These are then summed to give the total heat potential above the To - 2 isotherm for the grid square. The remainder of the heat potential between To - 2 and 26°C was then calculated by construction on 10x10 graph paper. The gradient for this final section was taken to be linear.

As a check, ten random temperature-depth relationships were computed by an independent observer, both by this method, and by the equal area method. The percentage difference found was on the order of 3 1/2%. Since the order of magnitude of total heat potential per degree square was 10^3, 10^4, the accuracy of the nomogram method is taken to be 0.035 x (10^3, 10^4), or plus or minus 35-350 gm-cal/cm^2 with respect to the equal area method.

The precision of the nomogram is plus or minus 20 gm-cal/cm^2 based upon the largest scale (44) and the ability to read to the nearest 1/4 of a gradation. For those grid squares having only a single observation, the heat potentials were computed entirely by construction because of the inaccuracy introduced by an isothermal layer when using Simpson's Rule.

The following is an illustration of the method used for determining the average heat potential per square centimeter for each grid square; data is from Appendix B.

(1) Surface temperature is 28.8°.

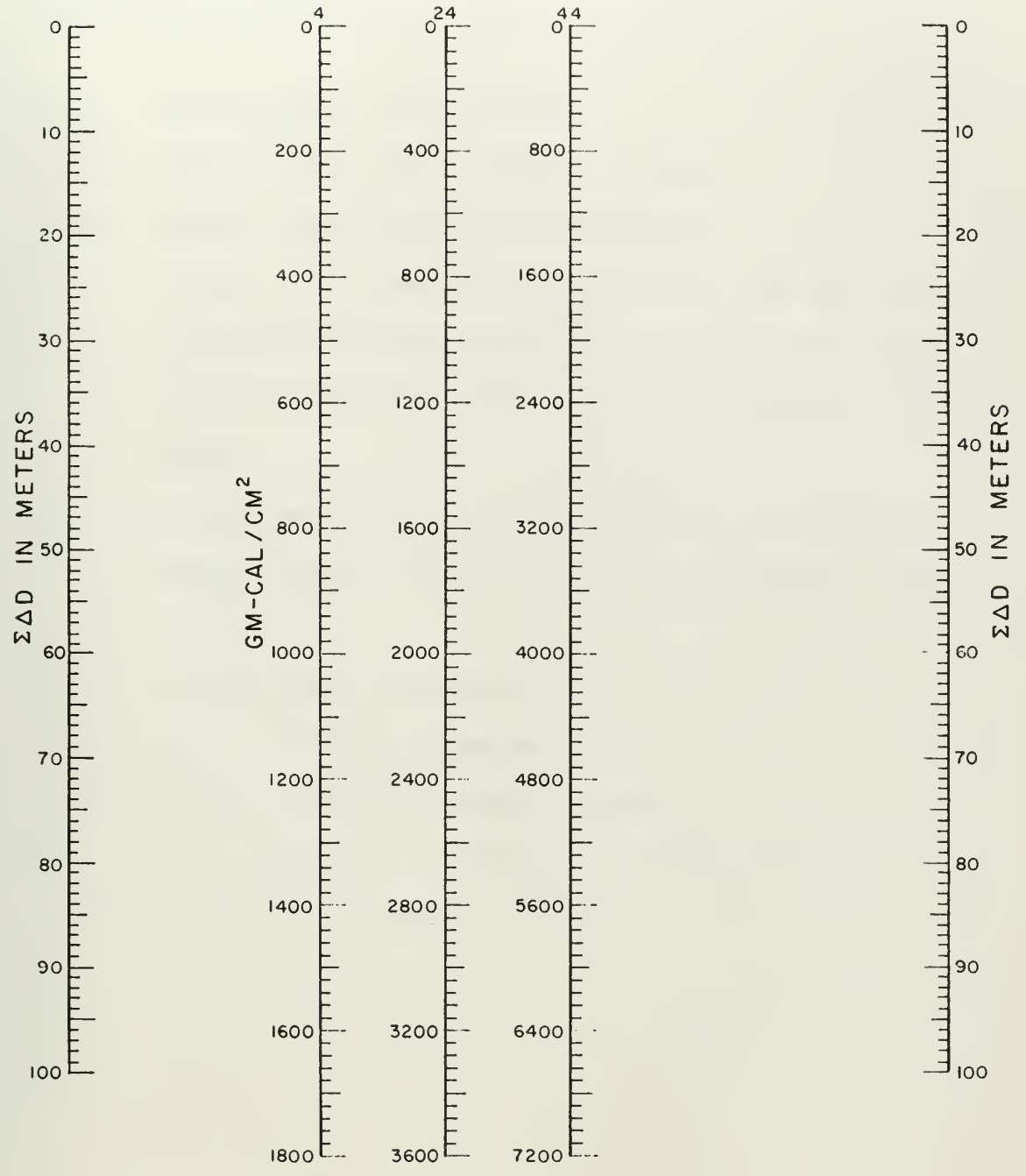
(2) Therefore the nomogram was used to determine heat potential between 28.8°C (To) and 26.8°C (To - 2).

(3) Heat potential between To - 2 and 26°C was determined by construction on 10x10 graph paper. This value was equal to 3680 gm-cal/cm^2.

Depth	Scale	Value from Nomogram
0	4	0
40	44	2680
42	24	1400
43	44	2880
45	4	750
Total:		7710 gm-cal/cm^2

(4) 7710 + 3680 = 11,390 gm-cal/cm^2, which was the accepted value for the heat potential of grid square 26-89 (Post-Betsy).

FIGURE C-1



HEAT POTENTIAL NOMOGRAM

APPENDIX D

DEFINITION OF SYMBOLS

Definition of symbols used in appendices E, F, G.

$\bar{D}_{26}$: Average depth of 26° isotherm.

Dmax: Maximum depth of 26° isotherm recorded.

Dmin: Minimum depth of 26° isotherm recorded.

$\bar{Q}$: Average heat potential above 26° isotherm in gm-cal/cm^2.

Q_1: Average heat potential in 10^{-3}gm-cal/cm^2 in those grid squares falling within the area of investigation. Prior Betsy.

Q_2: Average heat potential in 10^{-3}gm-cal/cm^2 in those grid squares falling within the area of investigation. After Betsy.

$\bar{T}_s$: Average surface temperature in °C.

Tsmax: Maximum surface temperature recorded.

Tsmin: Minimum surface temperature recorded.

X: $(Q_1 - Q_2)$ x Size. The amount of change in heat potential within a grid square in 10^{-16}gm-cal.

APPENDIX E

PRE-BETSY HEAT POTENTIALS

The values indicated below are those observed and computed values, by location, prior to hurricane Betsy. For definition of symbols, see Appendix D.

Location	No. BT's	$\bar{T}s$	Tsmax	Tsmin	$\bar{D}_{26}$	Dmax	Dmin	$\bar{Q}$
LAT 22-								
Lo-84	4	29.6	29.7	29.2	111	120	95	19,650
85	8	28.8	29.3	28.4	61	100	29	11,470
86	1	29.0	-	-	48	-	-	10,860
87	33	29.6	30.8	27.8	24	45	5	5,910
88	14	28.4	29.0	27.5	11	17	7	2,070
89	9	30.8	31.2	29.8	27	36	15	7,680
90	9	28.7	29.6	27.6	34	57	21	7,000
91	2	29.8	29.9	29.6	58	58	58	17,900

PRE-BETSY

Location	No. BT's	$\bar{T}s$	Tsmax	Tsmin	$\bar{D}_{26}$	Dmax	Dmin	$\bar{Q}$
LAT: 23								
Lo-85	9	28.9	29.4	28.4	39	73	27	7,560
86	12	29.8	30.2	29.3	62	90	41	15,440
87	18	29.7	30.2	29.5	46	61	25	11,510
88	2	29.5	29.5	29.5	43	44	42	10,490
91	2	29.1	29.1	29.0	51	55	47	13,210
LAT: 24								
Lo:85	10	29.4	30.2	28.3	59	76	42	13,540
86	17	30.5	31.0	29.7	101	135	76	22,320
87	9	30.2	31.0	29.2	123	150	82	21,560
88	8	29.1	29.3	28.9	93	108	39	19,620
90	6	29.5	29.7	29.3	42	45	39	12,590
91	6	29.2	29.3	29.2	43	46	41	11,450
92	6	28.5	28.6	28.4	57	62	52	11,860
93	11	28.7	28.9	28.4	54	59	50	12,420

PRE-BETSY

Location	No. BT's	$\bar{T}s$	Tsmax	Tsmin	$\bar{D}_{26}$	Dmax	Dmin	$\bar{Q}$
LAT: 25								
Lo:84	8	29.4	29.9	28.7	53	65	45	12,700
85	9	29.6	30.1	28.6	59	94	40	13,460
86	14	29.8	30.2	29.3	116	130	102	22,340
87	2	29.6	29.6	29.6	114	115	112	22,550
88	9	29.1	29.3	28.9	92	106	75	16,720
89	14	29.1	29.6	28.6	51	79	29	10,710
90	5	29.0	29.4	28.7	42	40	44	10,640
91	6	29.0	29.2	28.8	34	29	37	5,830
92	8	28.8	29.2	28.6	46	50	40	10,580
93	5	28.5	28.6	28.4	50	53	46	10,340

PRE-BETSY

Location	No. BT's	$\bar{T}s$	Tsmax	Tsmin	$\bar{D}_{26}$	Dmax	Dmin	$\bar{Q}$
LAT: 26								
Lo:84	3	29.7	29.9	29.6	47	50	43	10,510
85	1	29.7	-	-	40	-	-	10,630
87	11	29.7	29.9	29.5	91	120	60	20,080
89	13	29.1	29.4	28.7	49	68	38	11,130
90	7	29.0	29.2	28.9	42	46	32	10,030
93	6	29.7	30.4	29.3	48	52	43	14,390
LAT: 27								
Lo:87	9	29.1	29.5	28.6	50	61	41	12,340
90	1	28.6	-	-	47	-	-	10,250
91	6	29.2	29.5	28.7	44	50	38	10,540
92	2	29.2	29.1	29.2	40	40	40	10,610
93	6	30.1	30.4	29.8	46	48	42	14,520

PRE-BETSY

Location	No. BT's	$\bar{T}s$	Tsmax	Tsmin	$\bar{D}_{26}$	Dmax	Dmin	$\bar{Q}$
LAT: 28								
Lo:87	8	28.8	29.0	28.4	43	47	39	8,620
88	4	28.7	29.0	28.4	40	43	39	8,610
89	5	28.8	29.3	28.4	32	40	25	7,530
90	4	29.5	29.7	29.1	38	44	33	9,960
91	6	29.7	30.1	29.2	39	42	36	6,280
92	9	29.5	29.9	29.0	37	42	31	10,340
93	11	29.3	29.5	29.0	35	40	31	9,300
LAT: 29								
Lo:86	5	29.1	29.5	28.6	43	47	37	11,040
87	4	28.7	29.0	28.3	43	52	36	8,910
88	1	28.6	-	-	40	-	-	8,290
89	1	28.5	-	-	37	-	-	7,310

APPENDIX F

POST-BETSY HEAT POTENTIALS

The values below are those observed and computed values, by location, after Hurricane Betsy. For definition of symbols, see Appendix D.

Location	No. BT's	$\bar{T}s$	Tsmax	Tsmin	$\bar{D}_{26}$	Dmax	Dmin	$\bar{Q}$
LAT: 24								
Lo:86	9	28.3	28.6	28.0	55	81	46	8,490
87	12	28.3	28.9	27.8	93	110	75	14,290
LAT: 25								
Lo:85	7	28.1	28.2	27.8	51	66	34	10,340
86	8	28.5	29.0	27.9	77	107	47	13,840
LAT: 26								
Lo:84	12	27.6	28.0	27.0	38	50	24	3,820
85	7	27.9	28.3	27.5	67	88	48	9,600
86	8	28.5	28.6	28.3	95	102	79	16,300
87	9	28.6	29.0	28.1	95	118	75	18,210

POST-BETSY

Location	No. BT's	$\bar{T}s$	Tsmax	Tsmin	$\bar{D}_{26}$	Dmax	Dmin	$\bar{Q}$
LAT: 26								
88	6	28.4	28.9	28.2	47	55	40	11,090
89	5	28.8	29.0	28.5	47	54	42	11,390
90	9	28.5	28.9	28.2	43	53	32	8,920
LAT: 27								
Lo:86	4	28.3	29.0	28.0	72	96	55	11,400
87	13	27.6	28.2	26.9	45	66	23	5,470
88	4	28.3	28.4	28.0	55	62	46	10,630
89	6	28.0	28.8	27.4	49	54	38	7,410
90	5	29.2	29.6	28.7	45	52	42	9,730
91	2	29.4	29.5	29.2	45	46	44	10,740
LAT: 28								
Lo:86	5	28.7	28.9	28.6	84	87	82	18,400
87	18	28.4	29.0	27.5	64	80	50	11,840
88	10	28.2	28.9	27.5	57	65	48	9,270

POST-BETSY

Location	No. BT's	$\bar{T}s$	Tsmax	Tsmin	$\bar{D}_{26}$	Dmax	Dmin	$\bar{Q}$
LAT: 28								
89	11	28.3	28.9	27.7	65	90	50	10,770
90	10	28.0	28.5	27.7	46	85	32	5,750
91	8	28.4	29.0	27.6	45	49	40	8,080
92	9	28.5	28.0	29.0	42	57	34	8,590
93	6	29.1	29.5	28.5	Isothermal			7,440
LAT: 29								
Lo:86	5	28.2	28.4	27.9	72	80	62	12,080
87	10	28.7	28.9	28.5	62	72	54	13,220
88	3	28.8	29.0	28.7	57	58	55	11,560

APPENDIX G

FINAL HEAT POTENTIAL VALUES

The values below are those final accepted values applied to the selected area of investigation. They were used to determine the total heat lost within this area.

Location	Size ($10^{-3}km^2$)	Q_1	Q_2	$(Q_1 - Q_2)$	X
24-85**	7.62	13.5	10.5	3.0	22.80
24-86	9.31	22.3	8.5	13.8	128.20
24-87	5.00	21.6	14.3	7.3	36.70
25-84**	1.78	12.7	8.5	4.2	7.47
25-85	10.84	13.5	10.3	3.2	34.67
25-86	10.84	22.3	13.8	8.5	92.14
25-87**	10.88	22.6	15.0	7.6	82.92
25-88	10.44	16.7	13.4	3.3	35.80
25-89**	3.26	10.7	12.2	-1.5	-4.90
26-84	6.87	10.5	3.8	6.7	46.03
26-85	10.88	10.6	9.6	1.0	10.88
26-86*	10.88	17.0	16.3	0.7	7.62
26-87	10.88	20.1	18.2	1.9	20.67
26-88*	10.88	14.9	11.1	3.8	41.34
26-89	10.36	11.1	11.4	-0.3	-3.11
26-90	1.78	10.0	8.9	1.1	1.96

Location	Size ($10^{-3}km^2$)	Q_1	Q_2	$(Q_1 - Q_2)$	X
27-83* **	1.95	10.0	10.0	0.0	0.00
27-84* **	10.88	10.5	7.5	3.0	32.64
27-85* **	10.88	10.5	10.0	0.5	5.44
27-86*	10.88	14.1	11.4	2.7	29.38
27-87	10.88	12.3	5.5	6.8	73.98
27-88*	10.88	10.0	10.6	-0.6	-6.53
27-89*	10.88	9.5	7.4	2.1	22.85
27-90	8.21	10.3	9.7	0.6	4.93
28-84* **	1.95	15.0	10.0	5.0	-9.75
28-85* **	6.42	11.4	18.0	-6.6	-42.30
28-86*	10.88	11.5	18.4	-6.9	-75.07
28-87	10.88	8.6	11.8	-3.2	-34.82
28-88	10.88	8.6	9.3	-0.7	-7.62
28-89	6.60	7.5	10.8	-3.3	-21.78
28-90	2.19	10.0	5.8	4.2	9.20
29-86	5.13	11.0	12.1	-1.1	-5.64
29-87	8.58	8.9	13.2	-4.3	-36.89
29-88	3.15	8.3	11.6	-3.3	-10.40
TOTALS					
34	274.60				488.81

* No observations prior Betsy.
** No observations after Betsy.

Average heat lost in entire area, per cm^2:

$$488.81 \times 10^{16} \text{gm-cal}/274.60 \times 10^{13} \text{cm}^2 = 1770 \text{ gm-cal/cm}^2$$

Average heat lost on a per day basis. Hurricane crossed area in 21.5 hours:

$$1770 \text{ gm-cal/cm}^2 \times 24 \text{ hours}/21.5 \text{ hours} = 1990 \text{ gm-cal/cm}^2\text{-day}$$

APPENDIX H

ESTIMATION OF WIND PROFILE

In order to properly determine the area of investigation, it was necessary to construct an estimated wind profile for Betsy. The data utilized in the construction was based upon estimations by Cry and De Angelis (1965), supplemented by the theoretical model of Malkus and Riehl (1960). The following assumptions were made:

(1) Average propagation speed of Betsy was 14.7 kts, based upon positions as indicated in Figure 9.

(2) Maximum surface winds attained were 130 kts. This wind regime occurred at a distance of 33 N.M. from hurricane center. The edge of the eye was about 16 N.M. from hurricane center. Wind speed was assumed to be 0 kts within the eye, and to increase linearly from the edge of the eye to the maximum wind regime region.

(3) The wind field was assumed to be circular in shape.

The data points for construction of the wind profile, obtained from the above sources, were determined to be as follows:

Distance from Hurricane Center (N.M.)	Wind Speed (kts)
16	0
33	130
48	109
64	87
88	65
125	50
150	46

From the above data a surface wind profile was constructed as a function of radial distance from storm center, along the radius perpendicular to the path of the storm on the right hand side. This profile was divided into linear segments as indicated in Figure H-1. The wind profile was then used to determine the average wind over the entire radial distance of 150 N.M.

Average Wind Speeds by Segment

Segment	Length (N.M.)	Average Wind Speed (kts)	Segment Boundaries (N.M. from center)
Eye	16	0.0	0 - 16
A	17	65.0	16 - 33
B	15	119.5	33 - 48
C	16	98.0	48 - 64
D	26	76.0	64 - 90
E	35	57.5	90 - 125
F	25	46.0	125 - 150

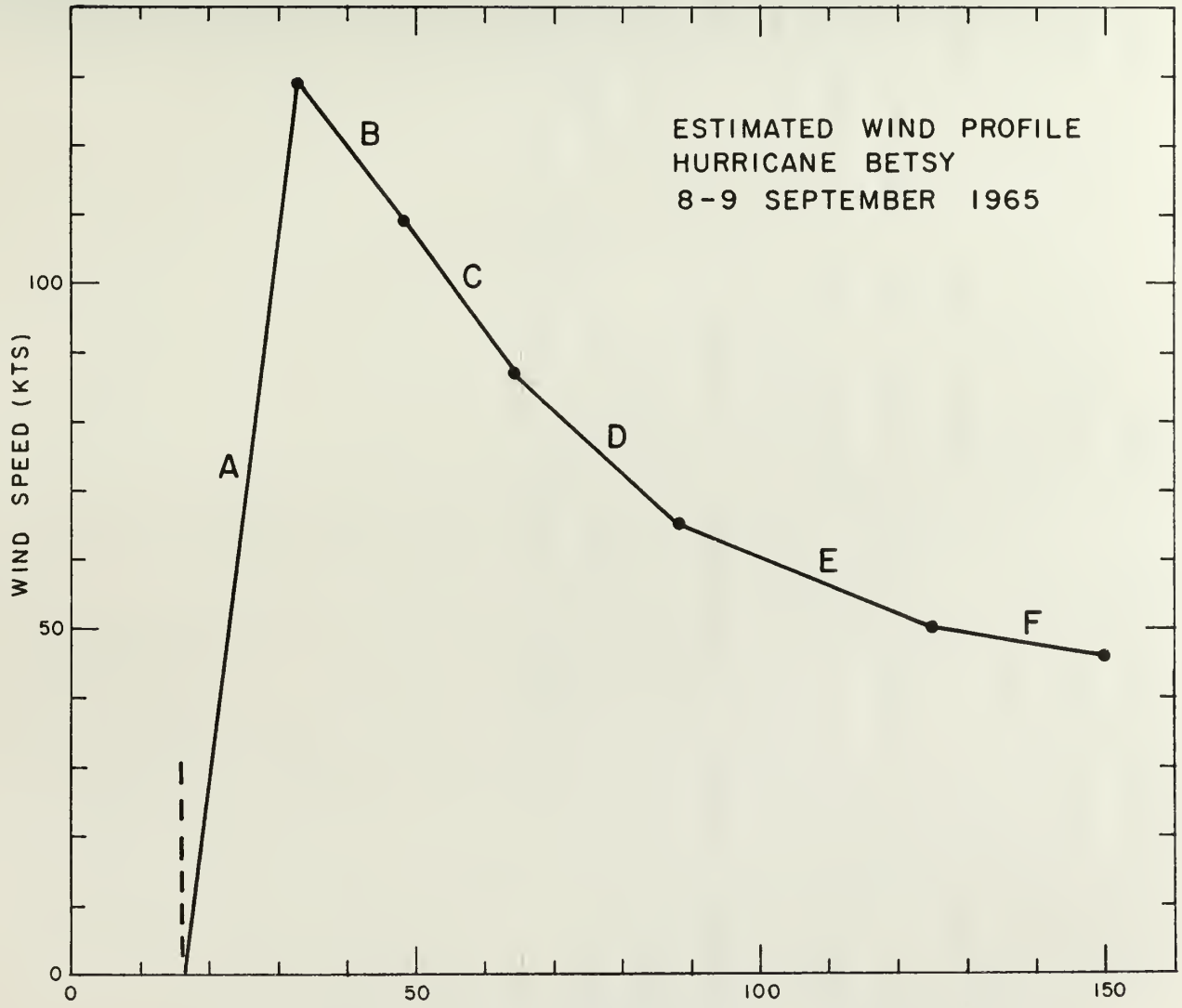

ESTIMATED WIND PROFILE
HURRICANE BETSY
8-9 SEPTEMBER 1965
WIND SPEED (KTS)
0
50
100
A
B
C
D
E
F
0
50
100
150
RADIAL DISTANCE FROM CENTER OF BETSY (NAUTICAL MILES)

FIGURE H-1

The average wind speed for the entire radial distance was computed to be 64.2 kts. Since this figure was computed along the radius of maximum wind velocity (i.e. these winds utilized the entire forward propagation speed component) the average wind speeds along the radii 90° to the right and left of this were 64.2 - 14.7, or 49.5 kts; the average wind speed along the opposite radius was 34.8 kts. Utilizing these four average wind speeds, the mean wind speed in the right semi-circle of the hurricane was computed to be about 57 kts, while that in the left was about 44 kts. The ratio of these two (57/44) is approximately 1.3:1. Therefore this was the ratio used in determining the distance from the mean path of Betsy to extend the area of investigation on the right side as compared to the left side.

APPENDIX I

CALCULATION OF RATES OF HEAT TRANSFER

Chapter III discussed the concept that rates of heat transfer vary directly with wind speed. This concept was used to estimate the rates of transfer at various distances from hurricane center. These calculations were based upon the wind profile in Appendix H, the computed average transfer rate of 1990 gm-cal/cm^2-day, and the utilization of the proportionality between heat transfer and wind speed.

Beginning at the center of the hurricane path and proceeding outward along any radial line, the average rate of heat transfer along such a line is 1990 gm-cal/cm^2-day, if the line terminates at a boundary of the selected area of investigation. In order to make calculations meaningful this line will be referred to as a band of 1 cm width. If the wind profile along such a band could be estimated, then, utilizing the concept of proportionality between wind speed and heat transfer, the heat transfer rates could be computed over various segments of the band based upon the following relationship:

$$\frac{\text{Avg. wind speed over entire band}}{\text{Avg. transfer rate over entire band}} = \frac{\text{Avg. wind speed over segment}}{\text{Avg. transfer rate over segment}}$$

This method was utilized to determine the average rates of heat transfer over the segments of such a band. The band, segments, wind profile, and average wind speeds are described in Appendix H.

The final results of the computations are shown below.

Segment	Avg. Wind Speed (kts)	Distance from Hurricane Center (N.M.)	Average Transfer rate ($gm\text{-}cal/cm^2\text{-}day$)
Eye	0	0 - 16	0
A	65	16 - 33	2020
B	119.5	33 - 48	3730
C	98	48 - 64	3070
D	76	64 - 90	2360
E	57.5	90 - 125	1790
F	46	125 - 150	1430

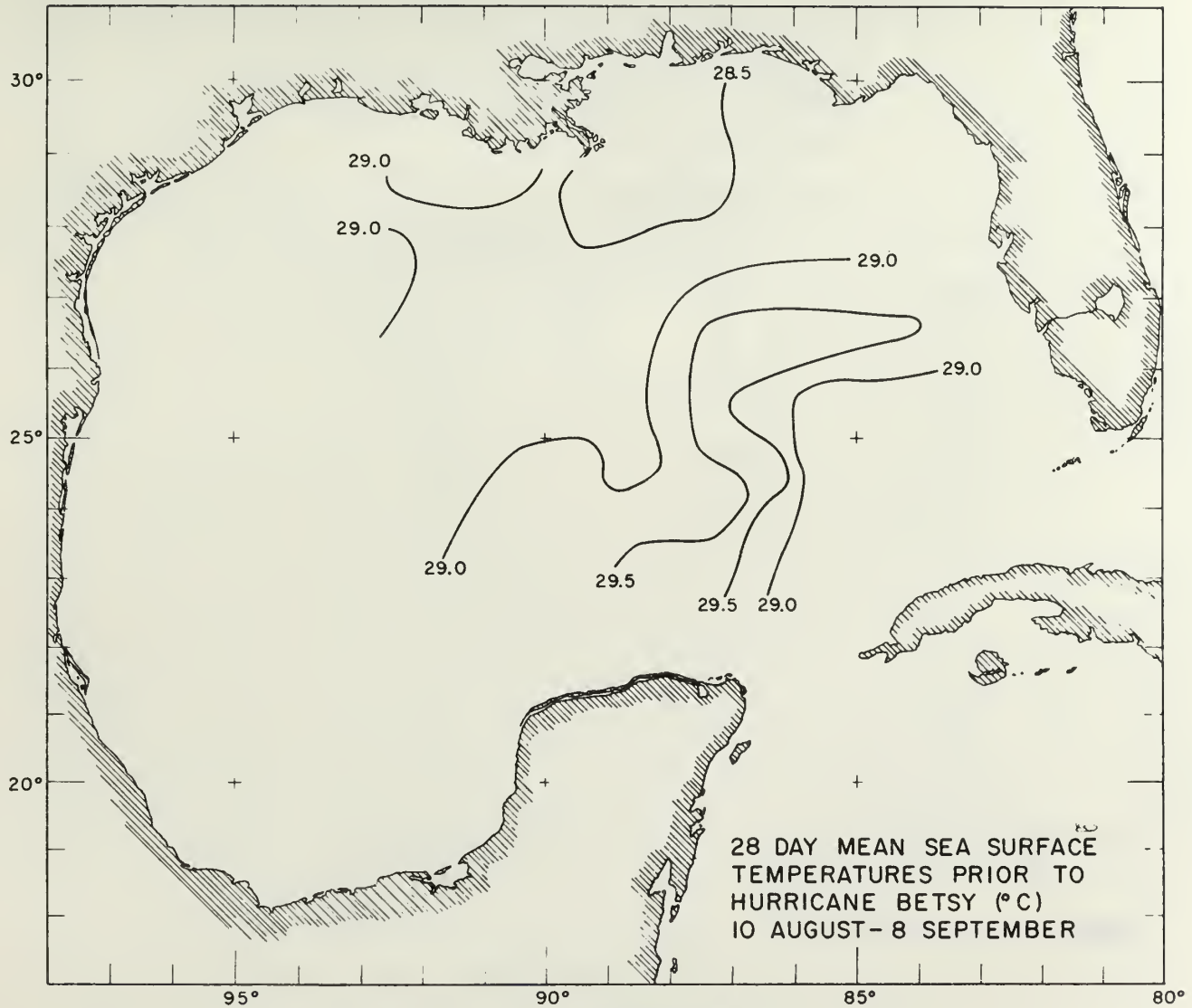

30°
25°
20°
95°
90°
85°
80°
28.5
29.0
29.0
29.0
29.0
29.0
29.5
29.5
29.0
28 DAY MEAN SEA SURFACE
TEMPERATURES PRIOR TO
HURRICANE BETSY (°C)
10 AUGUST - 8 SEPTEMBER

FIGURE 1

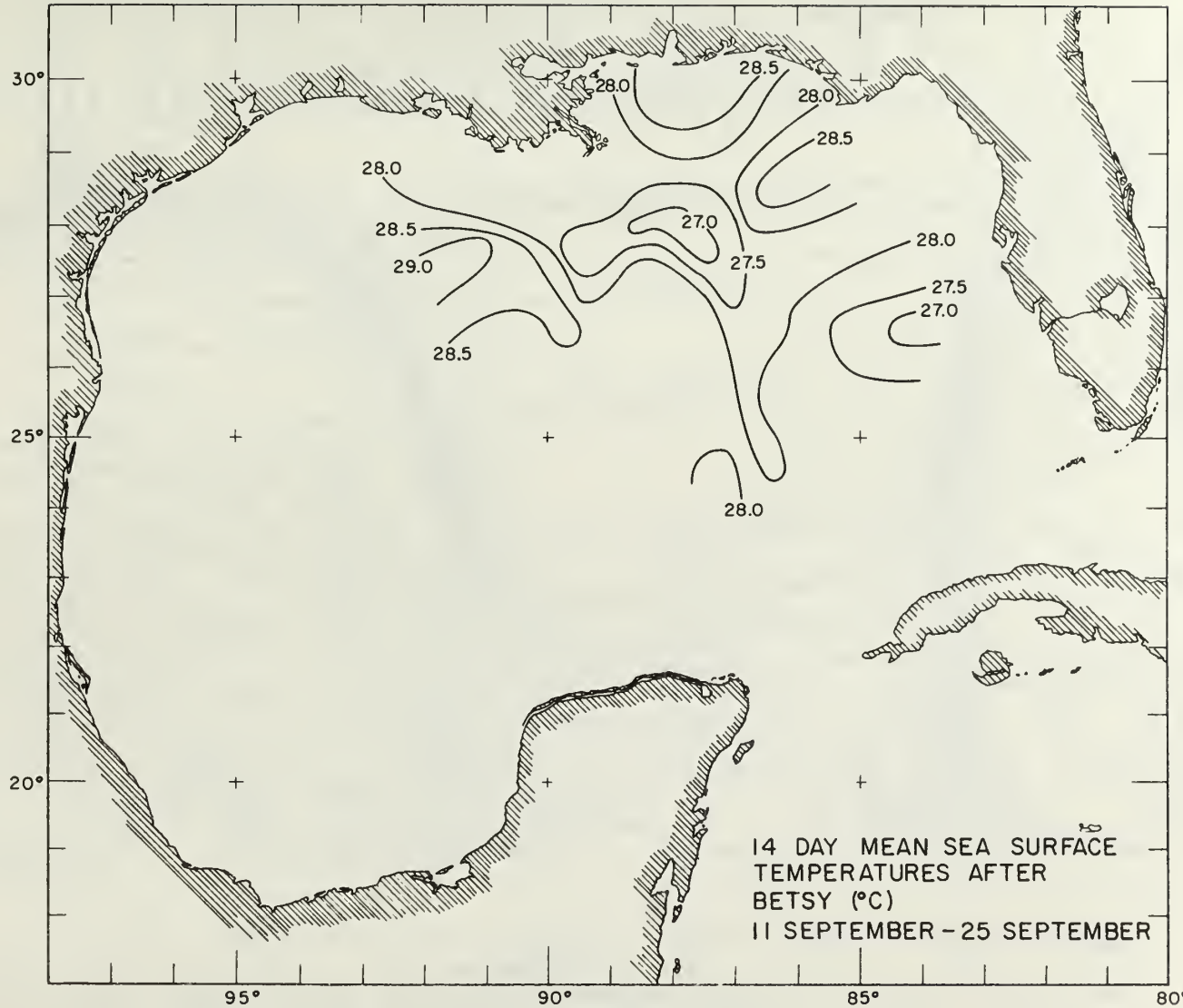
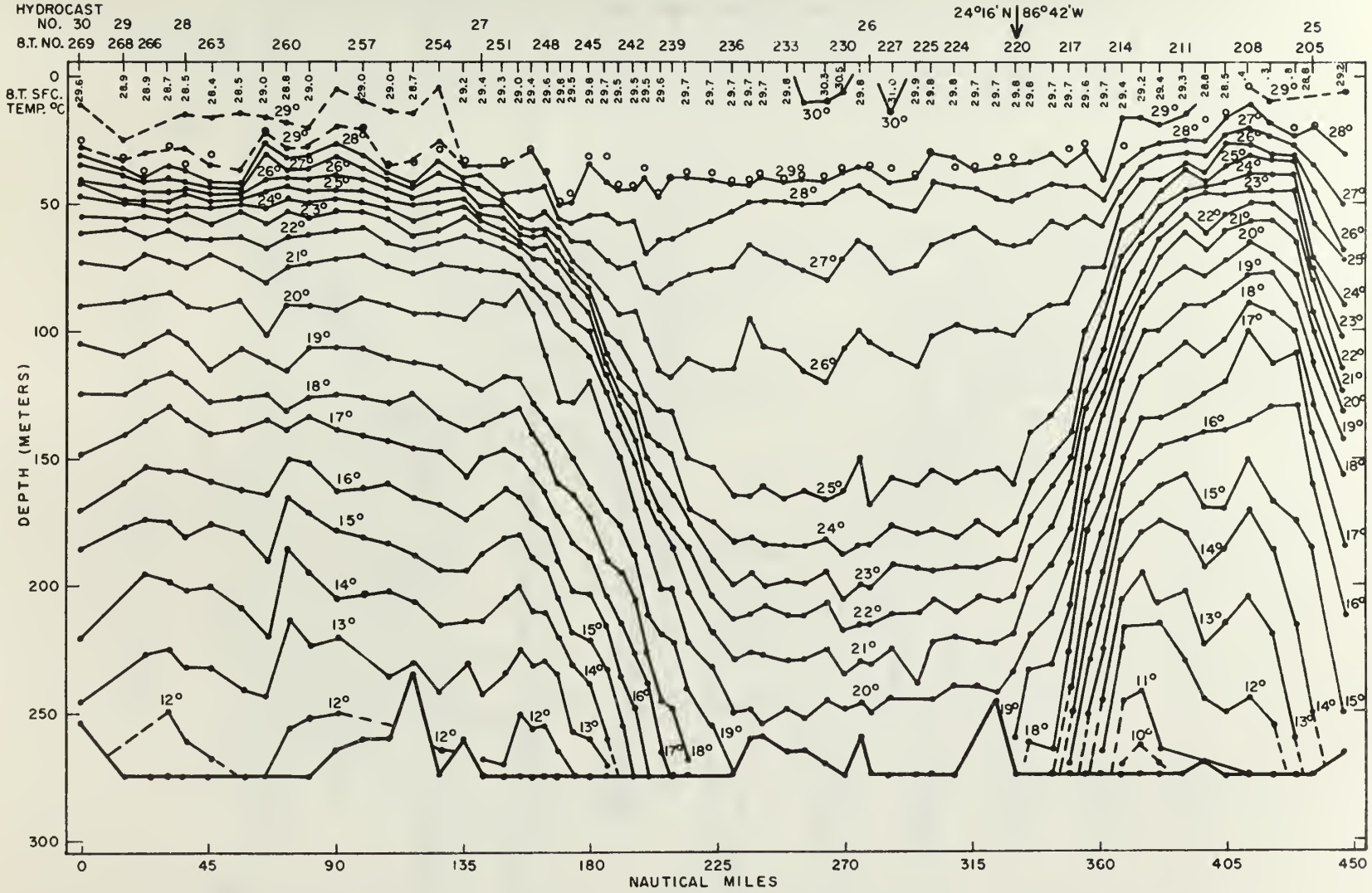

30°
25°
20°
95°
90°
85°
80°
28.0
28.5
28.0
28.5
28.0
28.5
29.0
28.5
27.0
27.5
28.0
28.0
27.5
27.0
14 DAY MEAN SEA SURFACE
TEMPERATURES AFTER
BETSY (°C)
11 SEPTEMBER - 25 SEPTEMBER

FIGURE 2



TEMPERATURE (°C) CROSS SECTION, LEG II, SOUTH FROM PANAMA CITY, FLA. 20-22 AUG. 1965

FIGURE 3 (After Leipper, to appear)

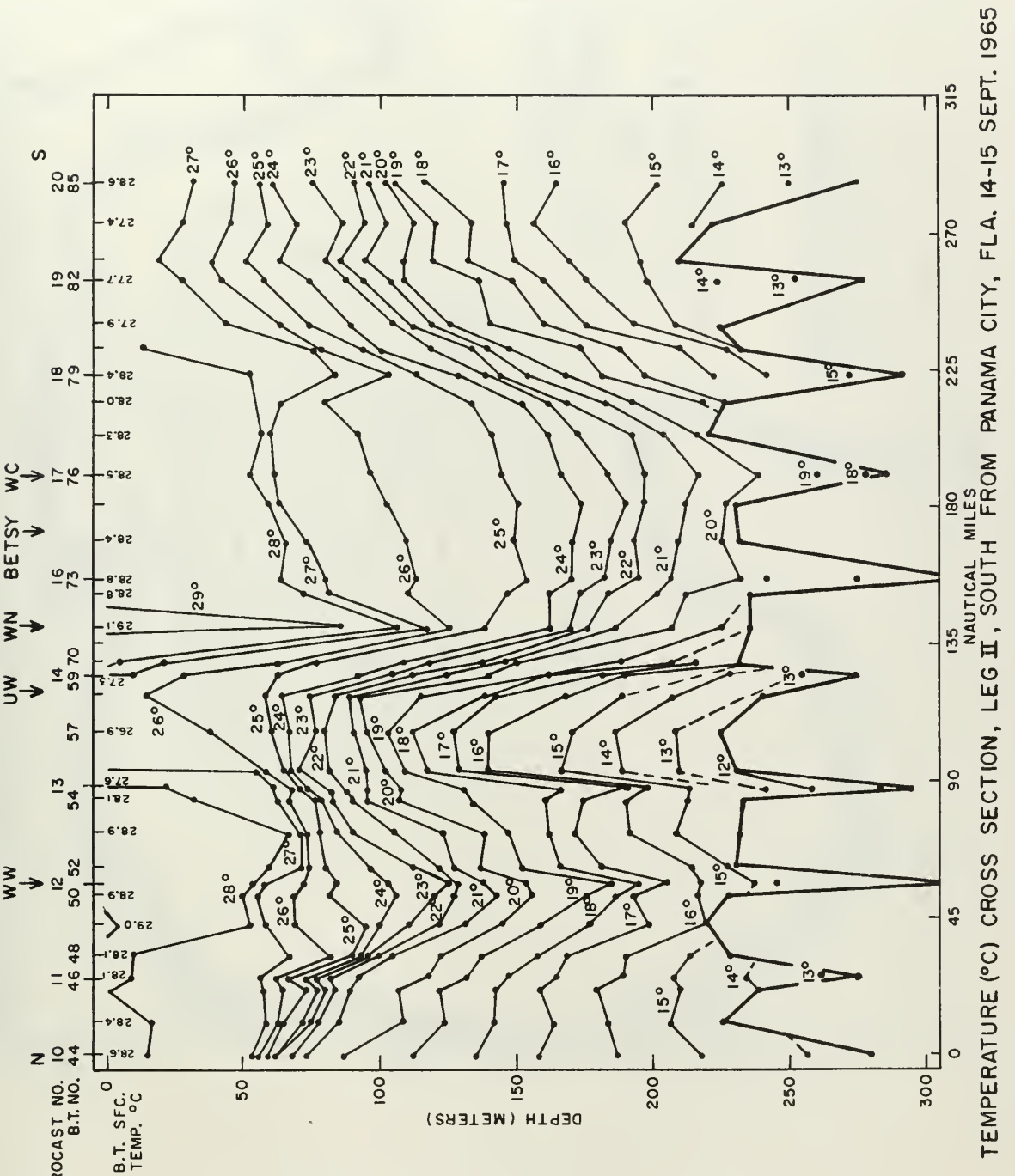


FIGURE 4 (After Leipper, to appear)

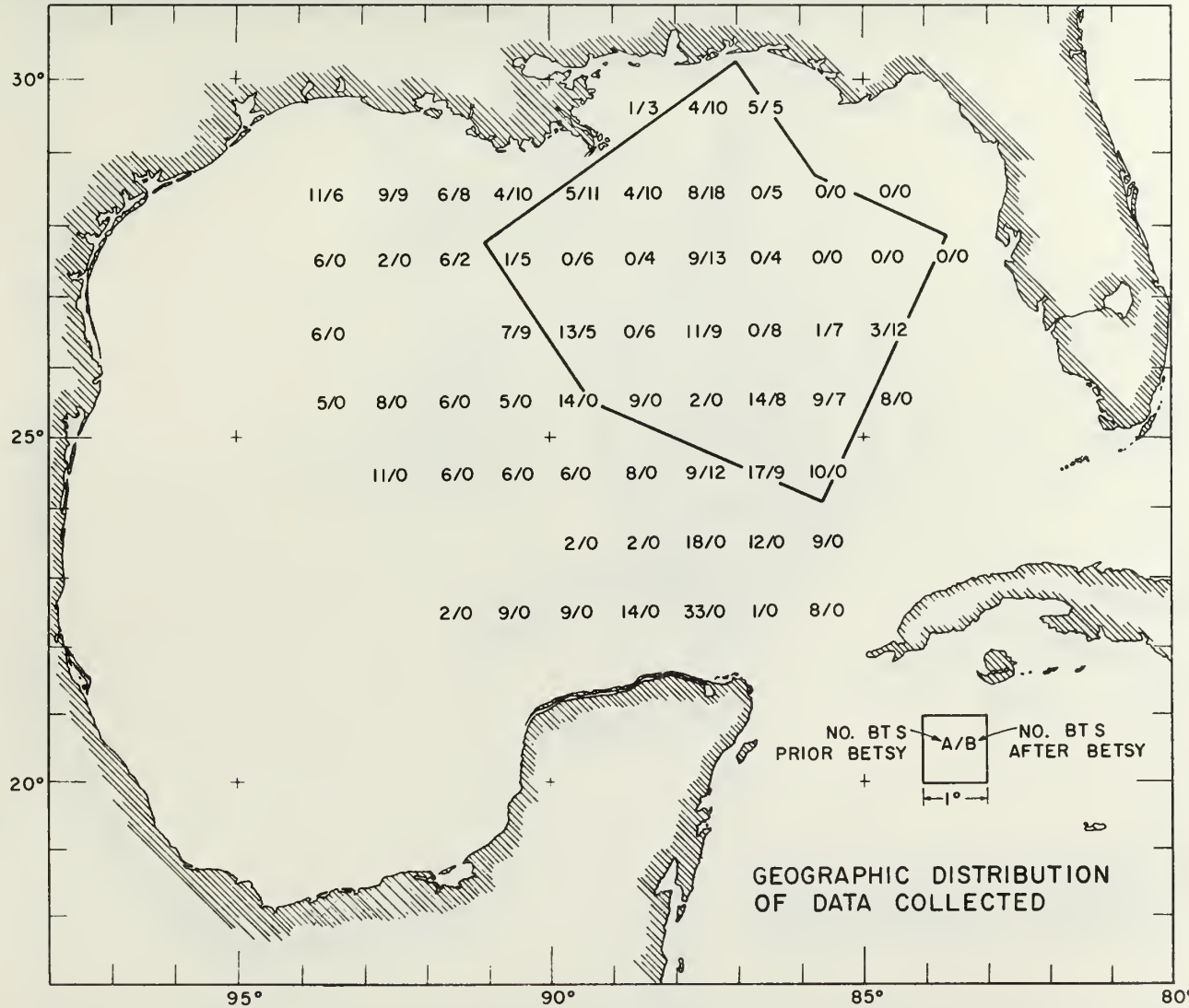

30°
25°
20°
95°
90°
85°
80°
1/3 4/10 5/5
11/6 9/9 6/8 4/10 5/11 4/10 8/18 0/5 0/0 0/0
6/0 2/0 6/2 1/5 0/6 0/4 9/13 0/4 0/0 0/0 0/0
6/0 7/9 13/5 0/6 11/9 0/8 1/7 3/12
5/0 8/0 6/0 5/0 14/0 9/0 2/0 14/8 9/7 8/0
11/0 6/0 6/0 6/0 8/0 9/12 17/9 10/0
2/0 2/0 18/0 12/0 9/0
2/0 9/0 9/0 14/0 33/0 1/0 8/0
NO. BTS PRIOR BETSY
A/B
NO. BTS AFTER BETSY
1°
GEOGRAPHIC DISTRIBUTION OF DATA COLLECTED

FIGURE 5

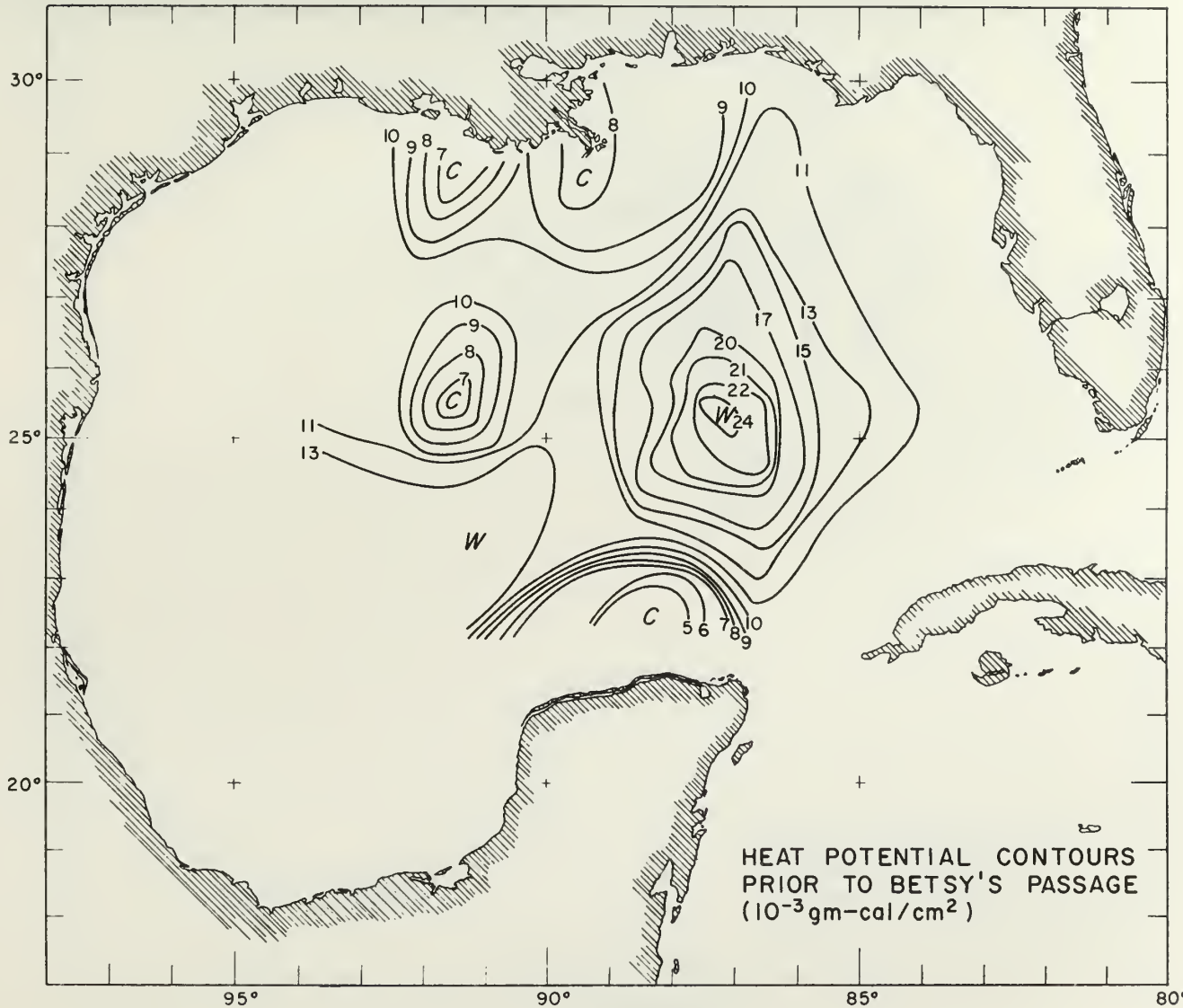

30°
25°
20°
95°
90°
85°
80°
HEAT POTENTIAL CONTOURS
PRIOR TO BETSY'S PASSAGE
(10⁻³ gm-cal/cm²)

FIGURE 6

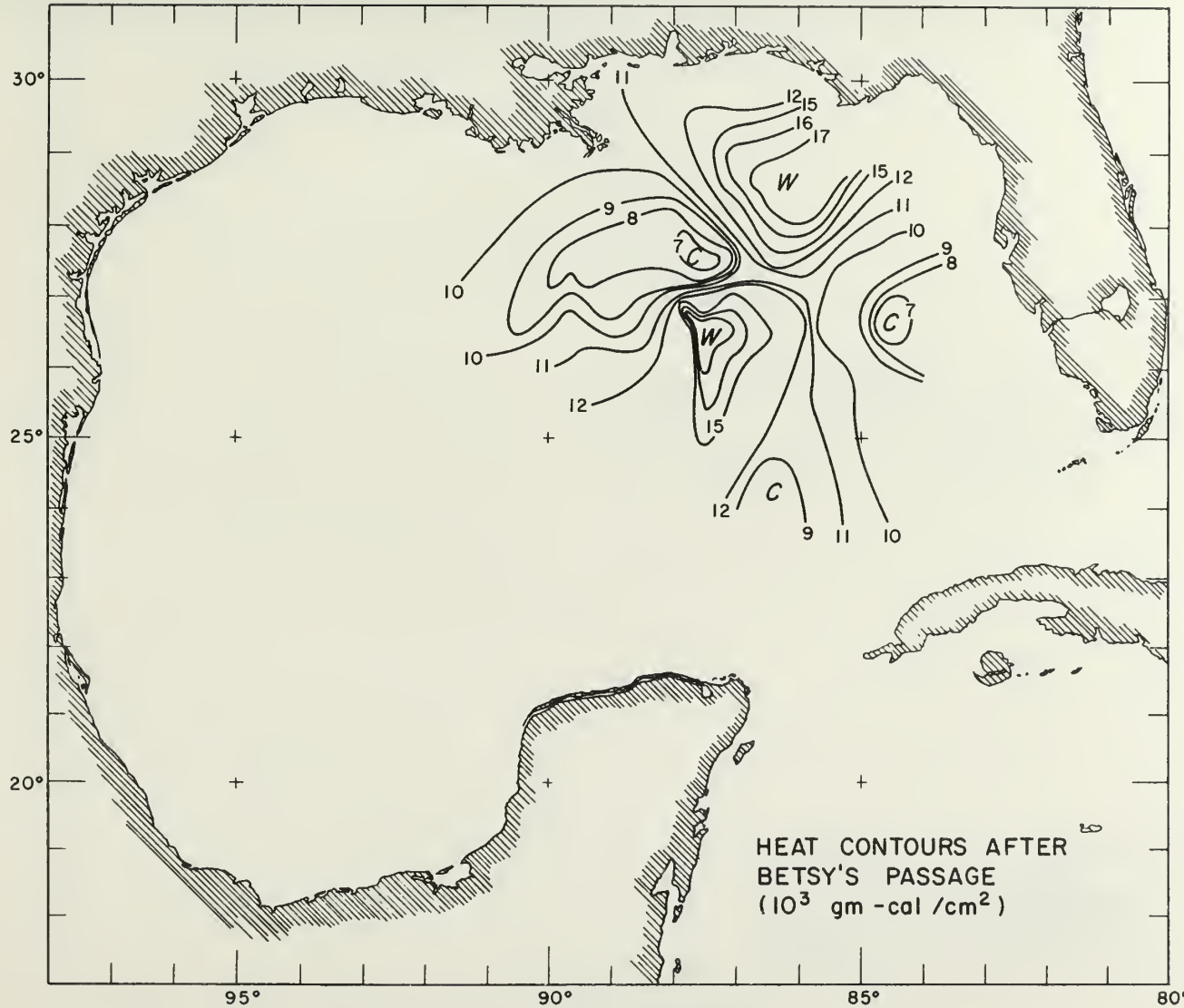

30°
25°
20°
95°
90°
85°
80°
11
12
15
16
17
W
15
12
11
10
9
8
C
10
9
8
C
10
11
12
W
15
12
C
9
11
10
HEAT CONTOURS AFTER
BETSY'S PASSAGE
(10³ gm -cal /cm²)

FIGURE 7

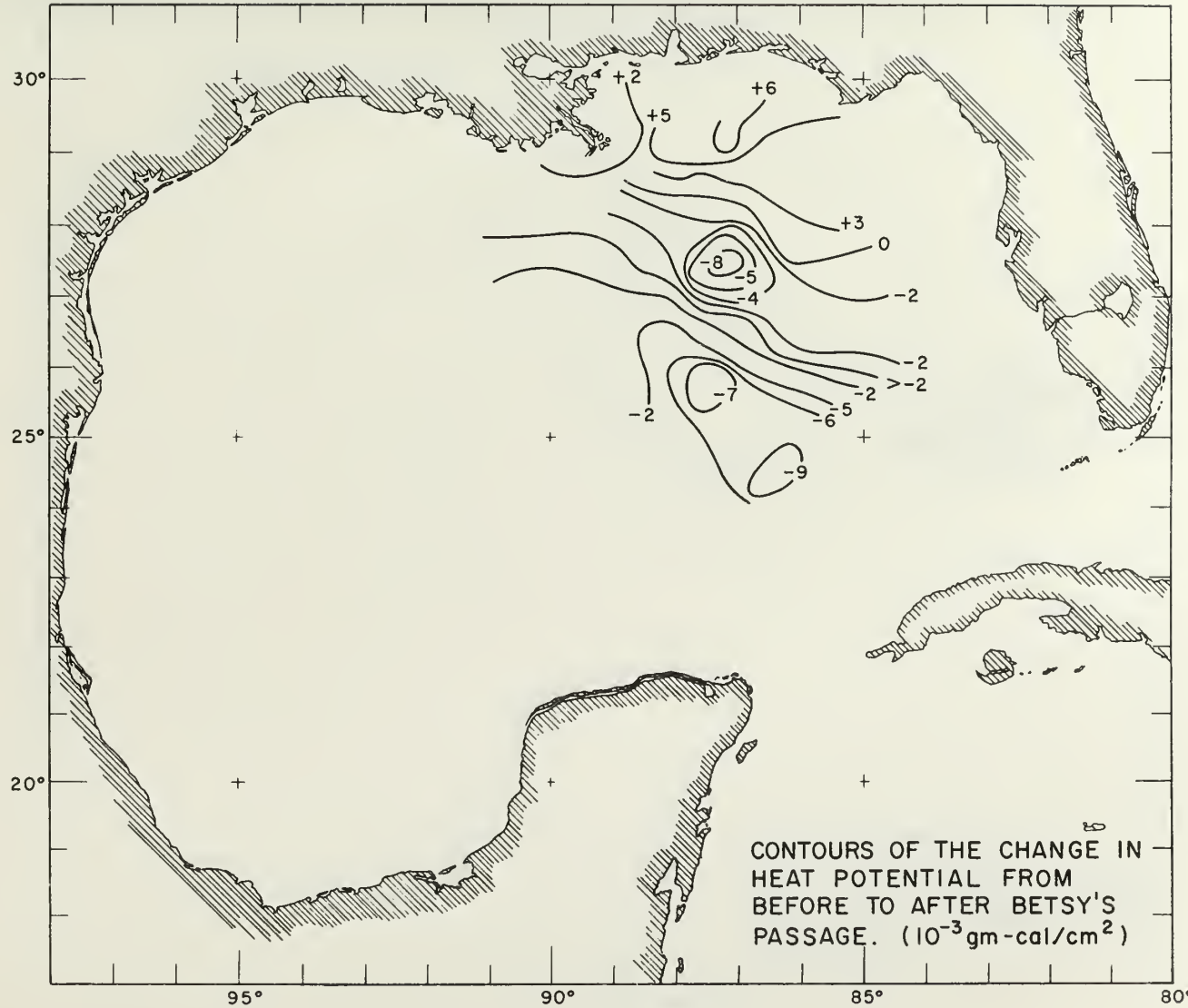

30°
25°
20°
95°
90°
85°
80°
+2
+6
+5
+3
0
-8
-5
-4
-2
-2
-2
>-2
-7
-2
-6
-5
-2
-9
CONTOURS OF THE CHANGE IN HEAT POTENTIAL FROM BEFORE TO AFTER BETSY'S PASSAGE. (10^{-3} gm-cal/cm^2)

FIGURE 8

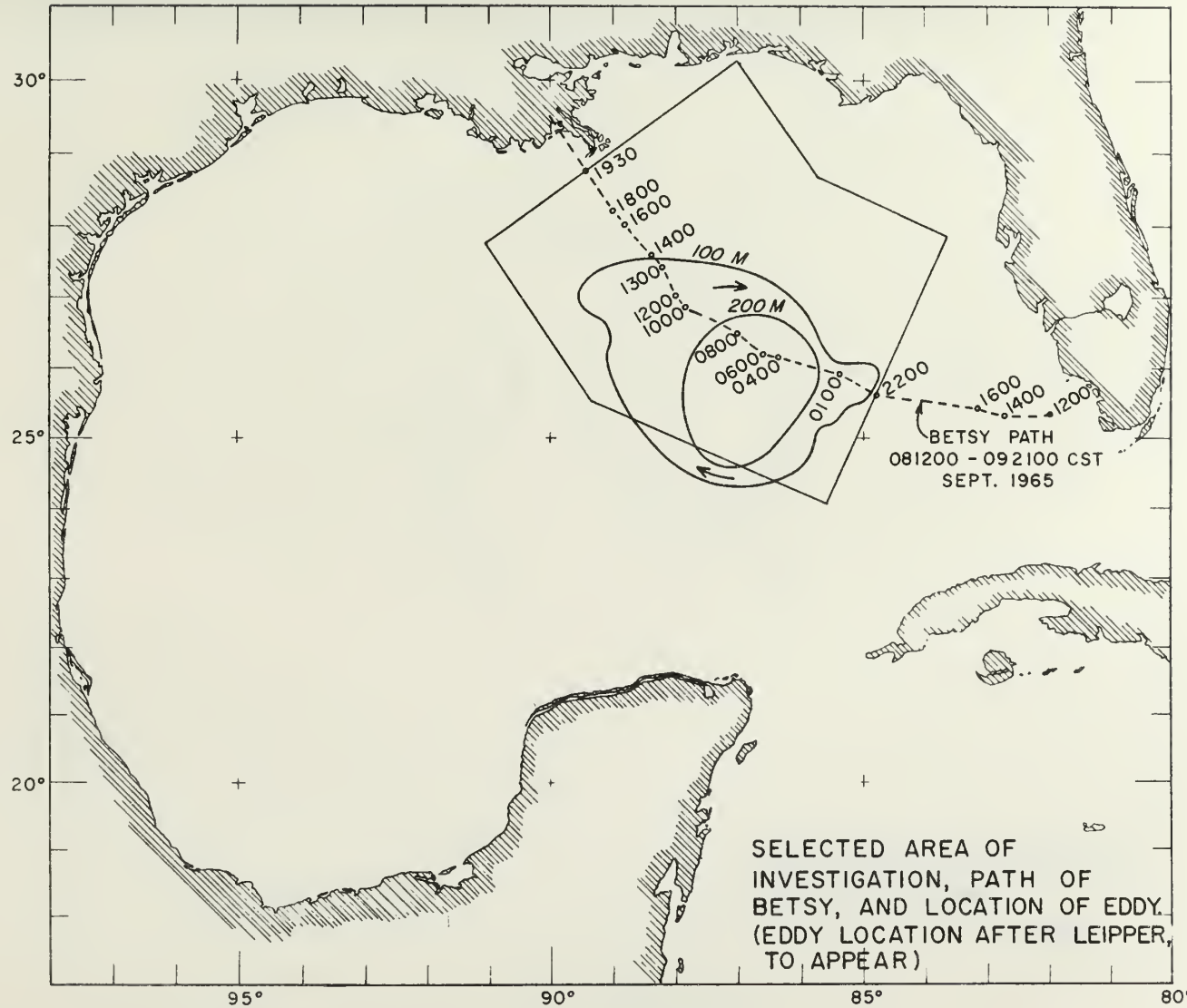

30°
25°
20°
95°
90°
85°
80°
1930
1800
1600
1400
1300
1200
1000
0800
0600
0400
0100
2200
1600
1400
1200
100 M
200 M
BETSY PATH
081200 - 092100 CST
SEPT. 1965
SELECTED AREA OF
INVESTIGATION, PATH OF
BETSY, AND LOCATION OF EDDY.
(EDDY LOCATION AFTER LEIPPER,
TO APPEAR)

FIGURE 9

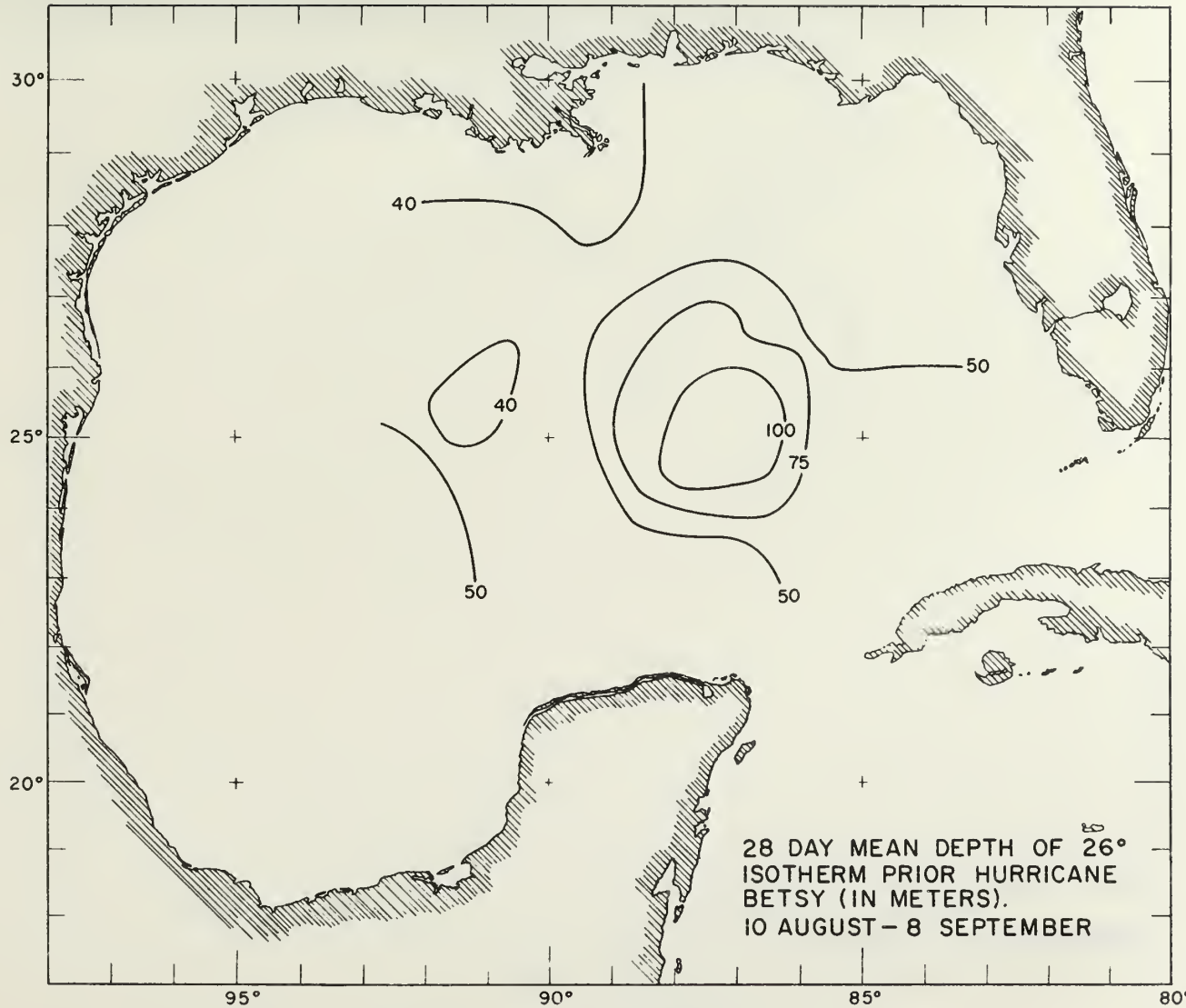

30°
25°
20°
95°
90°
85°
80°
40
40
50
100
75
50
50
28 DAY MEAN DEPTH OF 26° ISOTHERM PRIOR HURRICANE BETSY (IN METERS).
10 AUGUST – 8 SEPTEMBER

FIGURE 10

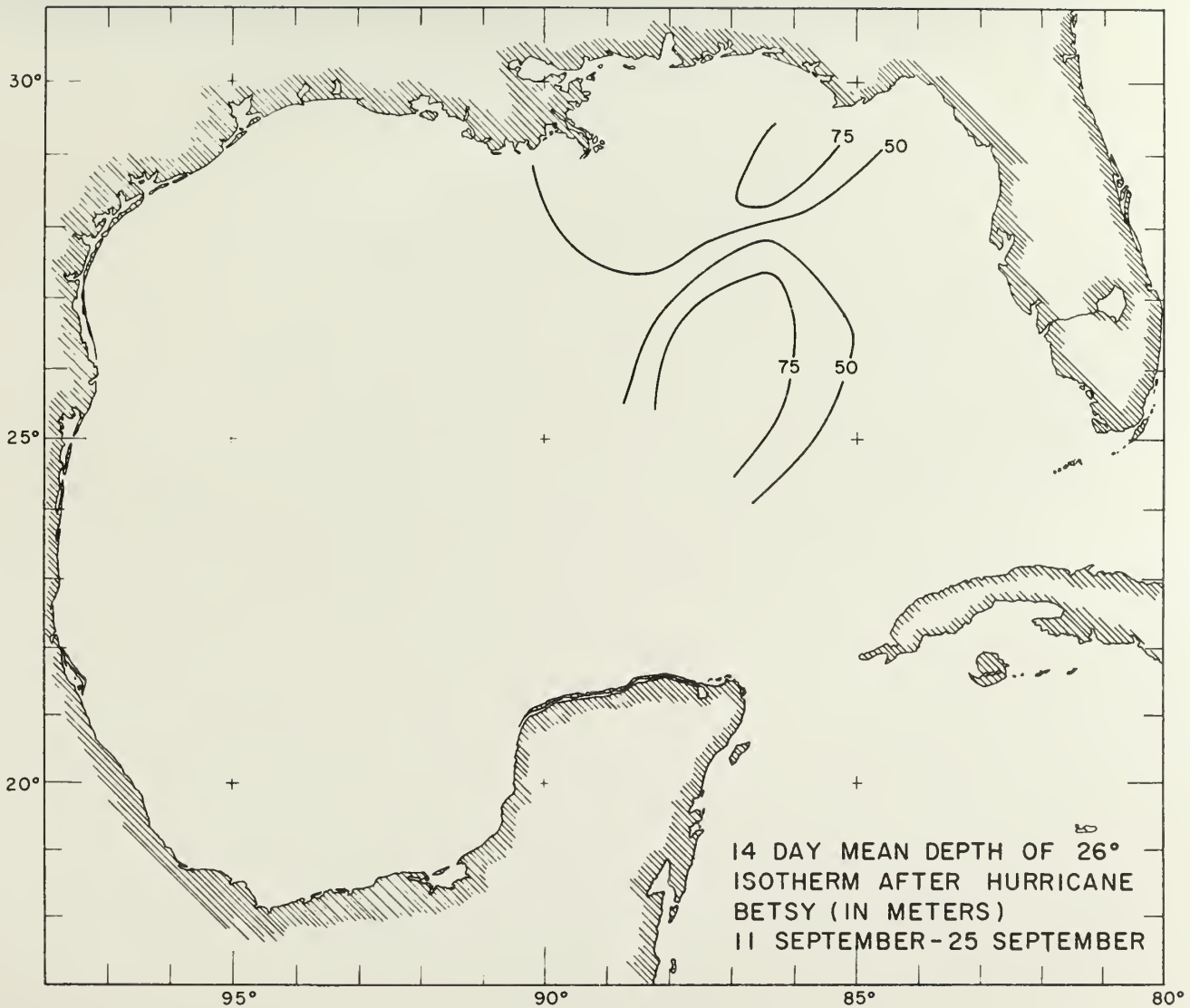

30°
25°
20°
95°
90°
85°
80°
75
50
75
50
14 DAY MEAN DEPTH OF 26° ISOTHERM AFTER HURRICANE BETSY (IN METERS)
11 SEPTEMBER-25 SEPTEMBER

FIGURE 11

thesW5507
Quantitative determination of heat trans
3 2768 001 95051 2
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